Web Crippling and Combined Bending and Web Crippling of Cold-formed Steel Box-beam Headers

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Abstract

Box-beam headers are commonly used in walls framed with cold-formed steel studs to span openings in bearing walls. Based on the results of previous experimental studies, it has been shown that box-beam headers subjected to interior one flange (IOF) loading have been conservatively designed. This paper presents the results of an ongoing experimental study conducted at the University of Missouri-Rolla to establish the web crippling strength of box-beam headers for an IOF loading condition. Box-beam header specimens were tested as a system consisting of two C-sections together with top and bottom track sections. The header configuration used in this study is defined in the AISI publication *Standard for Cold-Formed Steel Framing – Header Design* (2000). Tested as a system, it was found that the web crippling strength was greater than that for two independent, single web C-sections. Based on the results of this study, an adjustment factor was developed to modify the web crippling strength determined using the AISI Specification for single web C-sections. An interaction equation was also derived for combined bending and web crippling.

Introduction

Cold-formed steel has been used in building construction as early as the 1850's but it has only been widely used since the 1940's. In 1946, the American Iron and Steel Institute (AISI) developed and published the first edition of the *Specification for the Design of Cold-Formed Steel Structural Members.* The current edition year of the specification is 1996 with a supplement that was published in 1999.

Cold-formed steel as commonly used in conventionally framed building structures was the focus of this study. More specifically, this investigation concentrated on box-beam headers over openings in cold-formed steel framed bearing walls supporting gravity loads from floors or roofs.

Previous studies of header beams for residential construction by the National Association of Home Builders (1997) and Stephens (1999) established that header beams have web crippling

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strengths greater than what is predicted using the current AISI Specification (1996). The purpose of this experimental study was to develop a new design methodology for conventionally framed box-beam headers (Figure 1) subjected to an interior-one-flange (IOF) loading. The objective was to determine a methodology for accurately determining the web crippling strength of box-beam headers and likewise an appropriate interaction equation for combined bending and web crippling.

Current Design Approach for Box-Beam Headers

There are two publications that deal with the design and construction of cold-formed steel header beams. One is the Prescriptive Method (2000) and the other is the AISI Header Standard (2000). The Prescriptive Method covers the selection of headers and the fabrication of headers for framed bearing walls in residential construction. This document is not a specification for design, but contains design tables established based on the AISI Specification (1996) for specific standard spans and loading conditions. It is intended especially for use by designers and homebuilders in sizing structural members for specific criteria and is therefore limited in its application. The Header Standard is intended for header design using the appropriate provisions of the AISI Specification. The provisions of the Header Standard are not limited to residential construction, but are intended to be used industry wide. The method of header construction is the same in both the Header Standard and the Prescriptive Method.

The Header Standard (2000) provides both design and fabrication recommendations. The fabrication of headers is covered in Section A1.1.1. The design requirements for box-beam headers are covered in Section B2, which references the AISI Specification (1996). AISI Specification Section C3.1.1 for determining nominal bending strength is use to establish header moment capacity. Web crippling capacity is determined using AISI Specification section C3.4. Web crippling strength for box-beams is calculated using the equation appropriate for shapes having single, unstiffened webs. Header capacity for combined bending and web crippling is determined using Section C3.5 of the AISI Specification. Based on the available research, it has been shown that for header design, shear is not a governing design parameter either alone or in combination with bending. This conclusion is based upon the adherence to the required method of fabrication in section A1.1.1 (Header Standard, 2000) and to a single span loading condition.

Design Equations for Headers

The nominal flexural strength, M_n, of header beams is determined using Section C3.1.1(a) from the AISI Specification (1996). This section assumes that adequate lateral bracing is provided. Equation C3.1.1-1, the effective yield moment based on the sections strength, is used to calculate the nominal flexural strength:

$$M_n = S_e F_y \tag{1}$$

where

F_y = Design yield strength

S_e = Elastic section modulus of the effective section calculated with the extreme compression or tension fibers at F_y.

Web crippling strength, P_n, for headers is calculated using AISI Specification (1996) section C3.4. The nine different equations in this section of the AISI Specification (1996) will be replaced in the AISI Specification (North, 2001) with a single equation given by Equation 2, which was the calculation method used in this study.

$$P_n = Ct^2 F_y \sin\theta \left(1 - C_R\sqrt{\frac{R}{t}}\right)\left(1 + C_N\sqrt{\frac{N}{t}}\right)\left(1 - C_h\sqrt{\frac{h}{t}}\right) \tag{2}$$

where

P_n = Nominal web crippling strength for one web
C = Coefficient: 13 for single web C-sections.
C_R = Inside bend radius coefficient: 0.23 for single web C-sections.
C_N = Bearing length coefficient: 0.14 for single web C-sections.
C_h = Web slenderness coefficient: 0.01 for single web C-sections.
h = Flat dimension of web measured in plane of web.
N = Bearing length (3/4 in. minimum) (19 mm minimum).
R = Inside bend radius.
t = Web thickness.
θ = Angle between plane of web and plane of bearing surface ($45° \leq \theta \leq 90°$).

The coefficients apply in the use of this equation only when specific conditions are met for each type of section. For single web C-sections such as box-beam headers, $h/t \leq 200$, $N/t \leq 210$, $N/h \leq 2.0$, $R/t \leq 5.0$ and $\theta = 90°$ must be met.

The AISI Specification provides two equations for web crippling combined with bending, one for Allowable Stress Design (ASD) and one for Load and Resistance Factor Design (LRFD). The LRFD method equation is based on the equation developed from research at the University of Missouri-Rolla (Hetrakul and Yu, 1978 and 1980; Yu, 1981). For shapes having single unreinforced webs, the original equation (Eq. 3) is given in the AISI *Commentary* (1996).

$$1.07\left(\frac{P_{test}}{P_{ncomp}}\right) + \left(\frac{M_{test}}{M_{ncomp}}\right) \leq 1.42 \tag{3}$$

where

P_{test} = Concentrated load at failure
P_{ncomp} = Nominal strength for concentrated load in the absence of bending moment.
M_{test} = Bending moment at the point of application of P_{test}.
M_{ncomp} = Nominal flexural strength about the centroidal x-axis of the two C-sections independent of the attached tracks.

Experimental Investigation

This experimental investigation was initiated as a continuation of the pilot study (Stephens, 1999) and focused on additional testing of box-beam headers constructed as shown in Figures 1 and 2. All specimens were fabricated using industry standard material provided by three different manufactures of cold-formed steel construction products. Fabrication and testing was done at the University of Missouri-Rolla.

The mechanical properties of the steel used in each of the test specimens were determined by standard coupon tension tests using ASTM A370 procedures. Three coupons were taken from the web portion of one sample of each different section type used in this study, including the track. The coupons were taken at a location away from the bend between web and the flange so that the increased strength from cold work of forming would not influence the material properties. Each coupon was then tested to failure and values for yield stress, F_y, tensile strength, F_u, and percent elongation at fracture were determined.

Section properties of each specimen were determined using the provisions of the AISI Specification (1996). Cross section measurements of each different C-section and track were made and calculations were performed using CFSLT, Version 3.04 software to establish the area A, the effective section modulus S_e, gross moment of inertia I, and effective moment of inertia I_e, all about the strong axis of the sections. The effective section properties were made at the maximum stress equal to the yield stress of the material.

Test specimens were fabricated following the guidelines of the Header Standard (2000) for box-beam headers. Box-beam specimens were fabricated using two identical C-sections to form a "box" configuration and both solid web and C-sections with web holes were used. Spacing of screws to attach the top and bottom tracks to the C-section flanges are shown in Figure 3. Web stiffeners were also utilized at the reaction points of the specimens to prevent web crippling at the supports. The two C-sections were not attached together in any way other than the tie provided by the top and bottom tracks.

Two different loading configurations were used as shown in Figure 4. The single IOF loading configuration was used for most of the spans less than 4-foot (1.22 m) in length while the two IOF loading configuration was used for spans longer than 4-feet (1.22). The two IOF load point configuration was used for the longer spans for two reasons. First, in standard building framing, interior point loads on the header will usually be spaced at 16-inches (406 mm) or 24-inches (610 mm) on center. Therefore, spans longer than 4-feet (1.22 m) can be expected to support more than one point load. Second, by applying two symmetrically placed loads, maximum moment will be constant between the load application points as will the maximum compression force in the top track and flanges of the C-sections.

A total of thirty-two box-beam specimens were tested in addition to the specimen data used from the pilot study (Stephens, 1999) for a total of 38 specimens. ¾-inch (19 mm) thick steel bearing plates that were not attached to the test specimens were used at the beam end supports and at the IOF load points. The length of bearing for the beam end reactions was 3-inches (76 mm) and 1 ½-inches (38 mm) for the IOF load points. At one end support a sliding bearing plate was used to allow horizontal movement of the support while the specimen was being loaded. The specimens were not attached to the supports or bearing plates by any means. Lateral bracing was provided at 24-inches (610 mm) on center spacing and at the end supports to prevent lateral-torsional buckling. Figure 5 shows a schematic of a test set-up for a specimen with two IOF load points.

Load tests were conducted on the header assemblies using a constant load application method. Deflection measurements at regular intervals were made to the nearest 1/1000 of an inch (0.0254 mm) using a dial gage. Load was applied at a steady rate of between 200 and 300 pounds (0.890 and 1.334 kN) per minute. The maximum load reached was recorded along with the measured deflection at that load.

Test Results

The pilot study (Stephens, 1999) had previously indicated that the web crippling strength of box-beam headers was generally greater than the strength if calculated as two single, unreinforced webs. However, Stephens also indicated that box-beam web crippling strength was less than that predicted by Equation 2 for built-up sections. Therefore, sufficient testing was needed to develop with certainty a new methodology to determine the web crippling strength of box-beam headers. Each box-beam header specimen was tested to failure. The maximum load resisted by each specimen was recorded and used to calculate the actual bending and web crippling strength of the headers.

The failure mechanism of all box-beam headers was by either web crippling or combined web crippling and bending. Typical failure patterns of box-beam header specimens are shown in Figures 6 and 7. These figures show that failure occurred at the load bearing point. Failure was generally symmetrical in that the webs of both C-sections failed in an identical manner directly below the bearing plate. This failure mechanism is very similar to that described by Yu (2000) for single unreinforced webs. In addition to the failure of the two webs, it can be seen that there was significant inelastic deformation of the top track under the load bearing plate.

The calculation of the theoretical bending strength M_n, was accomplished using Equation 1. The section moduli used in these calculations are given in Table 1.

P_n is the web crippling strength of the header predicted by Equation 2 using coefficients for single unreinforced webs with stiffened or partially stiffened flanges, not fastened to the bearing plate or support, and then multiplied by two to account for the two webs that make up the header. P_n does not take into account any increase in web crippling strength that may be gained from the presence of the top track. The section properties used in the coefficients for Equation 2 are given in Table 1.

For the majority of box-beam specimens tested, C-sections without web penetrations were used. However, nine of the specimens had standard 1-1/2 inch (38 mm) by 4-inch (102 mm) web penetrations spaced at 24-inches (610 mm) on center along the C-section at the mid-height of the web. For each test using these sections, the center of the web penetration was positioned no closer than 12-inches (305 mm) from the center of the bearing plate at the reaction or the loading point. The web penetration reduction factor R_c, was determined to be 1.0 for this configuration using Equation C3.4.2-2 from the AISI Specification Supplement (1999) for interior-one-flange loading conditions.

Evaluation of Results – Web Crippling

In the pilot study (Stephens, 1999), P_n was calculated both as a single, unreinforced web and also as a built-up section for box-beams. The actual web crippling strength determined through tests generally fell somewhere between these two values. It was apparent that the top track and its limited attachment to the C-section flanges was providing additional web crippling strength but not to the same extent as for built-up sections.

To evaluate the web crippling strength of box-beam headers, P_n based on Equation 2 for single, unreinforced webs was used as a base value to which a modifier representing the increase in web crippling strength for the box-header assembly would be applied.

To develop a modifier for P_n for box-beams, different relationships in materials of the track and C-sections were studied and evaluated. This was done in an effort to determine what parameters of the header components had an effect on P_n and best reflected the increase in web crippling strength that was evident from the tests. After evaluating different material relationships, it was determined that the ratio of track thickness to C-section thickness gave the best results in reflecting the changing web crippling strength of the box-beam header specimens. Table 2 gives the data used to develop the relationship between P_t/P_n and C-section t/track t. For this portion of the study, only those specimens of relatively short spans were used to evaluate P_n to minimize the effect of bending.

Using the relationship between the thickness of the C-section and the thickness of the top track, an empirical modifier was developed for Equation 2 by using the power curve relationship as shown in Figure 8. The power curve formula was rounded off and simplified to y = 2.3x or:

$$\frac{t_c}{t_t} = 2.3\left(\frac{P_t}{P_n}\right) \tag{4}$$

where

t_c = thickness of C-section
t_t = thickness of top track

With P_t and the thickness of the C-sections and track known, the new value of P_n hence referred to as P'_n, could be calculated. With the value of P'_n, the relationship P_t/P'_n was determined so that the mean value, standard deviation and coefficient of variation could be evaluated. This data is presented in Table 3. Based on these results, the following relationship for web crippling strength of box-beam headers is proposed:

$$P'_n = 2.3\left(\frac{t_t}{t_c}\right)P_n \geq P_n \tag{5}$$

where

Equation 2 is used to compute P_n
$0.3 \le (t_t/t_c) \le 1.0$

Values of Ω (ASD factor of safety) and ϕ (LRFD resistance factor) used for web crippling design were established according to the AISI Commentary (1996), Section F1. Calculations for Ω and ϕ were based on the mean value of P_t/P_n and the coefficient of variation of test results. Using a calibration program written by Baher Beshara (Version 1.1), Ω and ϕ were determined to be 1.82 and 0.84 respectively.

Evaluation of Results – Combined Bending and Web Crippling

AISI Specification (1996) Section C3.5 addresses the interaction between bending and web crippling for flexural members. Equation 3 was originally used to develop both the ASD and LRFD interaction equations C3.5.3-1 and C3.5.2-1 given in the AISI Specification for shapes having single unreinforced webs. Based on the evaluation of web crippling, a relationship was developed between M_t/M_n and P_t/P'_n to study the interaction between bending and web crippling for box-beam headers.

The data for M_t/M_n and P_t/P'_n is shown in Table 4. An interaction plot was then produced and compared with interaction Equation 3 and is shown in Figure 9. It was determined from the evaluation of Figure 9 that Equation 3 is conservative and therefore a different interaction equation would be appropriate for box-beam headers. The following interaction equation was proposed:

$$\left(\frac{P_t}{P'_n}\right)+\left(\frac{M_t}{M_n}\right)\le 1.5 \tag{6}$$

A plot of the test data in relation to Equation 6 gives an improved, but conservative correlation as can be seen in Figure 10. Most specimens were conservative, and those that were on the unconservative side were no less than 85% of the strength required. Therefore, based on the results of this experimental study, it is proposed that the web crippling strength of box-beam headers constructed as shown in Figure 1 be calculated using the empirical modifier as given by Equation 5. Additionally, it is proposed to use the new interaction formula given by Equation 6 for the loading condition of combined bending and web crippling.

From the evaluation of combined bending and web crippling, design equations for box-beam headers were developed for both ASD and LRFD design methods. To establish a design equation for combined web crippling and bending, a combined factor of safety, Ω, for ASD and a combined resistance factor, ϕ, for LRFD was established. This was done so that separate values of Ω and ϕ for web crippling and bending would not be necessary.

From Equation 6, the value of the term shown below

$$\frac{{}^{P_t}\!/\!{}_{P'_n}}{1.5}+\frac{{}^{M_t}\!/\!{}_{M_n}}{1.5} \tag{7}$$

was calculated for each of the test specimens. Statistical data generated from the evaluation of this term included the mean value, standard deviation and coefficient of variation (COV). Table 5 lists the interaction data used for each specimen including the results of the statistical analysis. The same calibration method and software used for web crippling was used for this evaluation. Using the mean value and the COV of the test results gave $\Omega = 1.79$ and $\phi = 0.86$.

Based on these results, the following formulas for the design of box-beam headers for combined bending and web crippling are proposed.

ASD:

$$\left(\frac{P}{P'_n}\right)+\left(\frac{M}{M_n}\right)\leq\frac{1.5}{\Omega} \tag{8}$$

where

$\Omega = 1.79$

LRFD:

$$\left(\frac{P}{P'_n}\right)+\left(\frac{M}{M_n}\right)\leq 1.5\phi \tag{9}$$

where

$\phi = 0.86$

The equations for web crippling and combined bending and web crippling for box-beam headers are applicable within the following limits: Track thickness ≥ 0.033-inches (0.838 mm), track flange width ≥ 1.0-inch (25.4 mm), C-section depth ≥ 6-inches (152 mm) and ≤ 12-inches (305 mm) and the C-section thickness ≥ 0.033-inches (0.838 mm) and ≤ 0.097-inches (2.464 mm).

Conclusions

The objective of this experimental study was to develop a new design methodology for conventionally framed box-beam headers subject to IOF loading. This was to be accomplished by experimental tests of headers as an assembly composed of two C-sections and two track sections. Based on the tests carried out for this study and for the previous pilot study (Stephens, 1999), the following conclusions have been developed:

- The nominal web crippling strength, P_n, for box-beam headers can be determined using Equation 2 with a modifier, Equation 5, depending upon the thickness of the top track and the C-sections. For design, Ω and ϕ were determined to be 1.82 and 0.84 respectively.

- The combined bending and web crippling strength for the design of box-beam headers can be determined using the interaction Equations 8 and 9 with $\Omega = 1.79$ and $\phi = 0.86$

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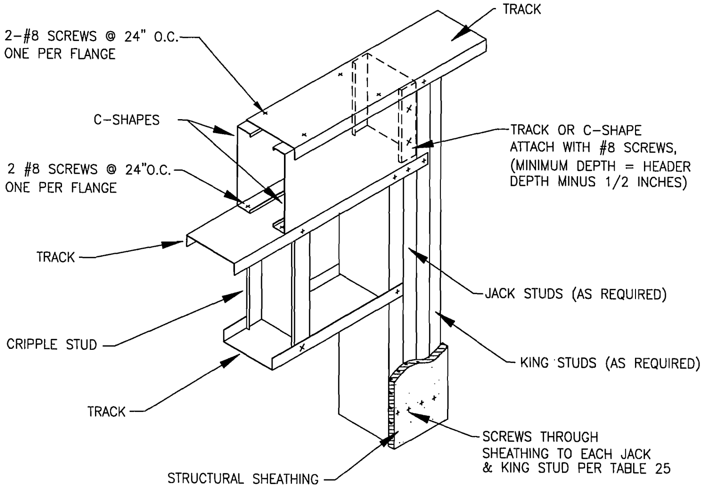

Figure 1. Box-Beam Header

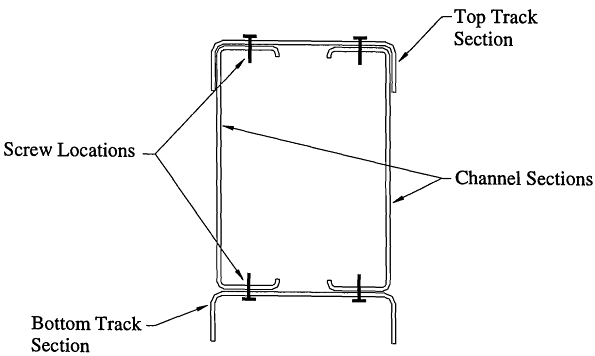

Figure 2. Box-Beam Header Cross-Section

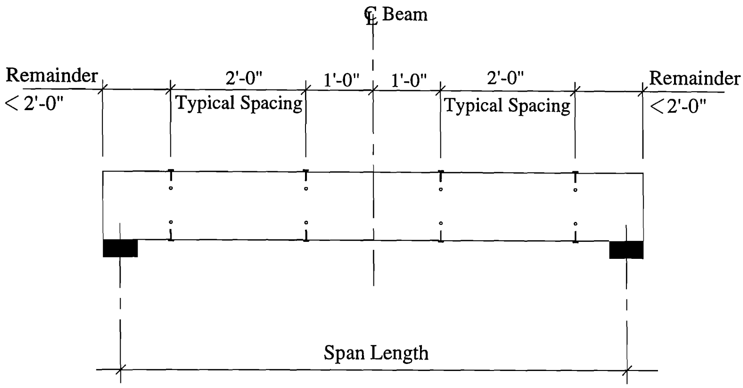

Figure 3. Typical Screw Spacing for Solid Web Test Specimens (1-foot = 305 mm)

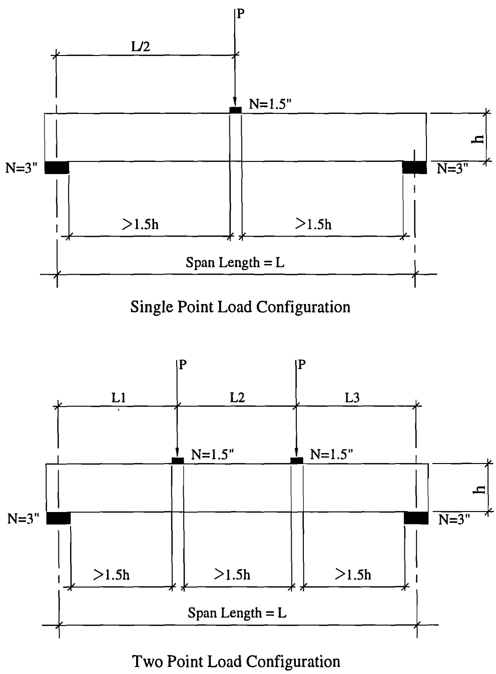

Figure 4. Typical Test Specimen Loading Configurations (1-inch = 25.4 mm)

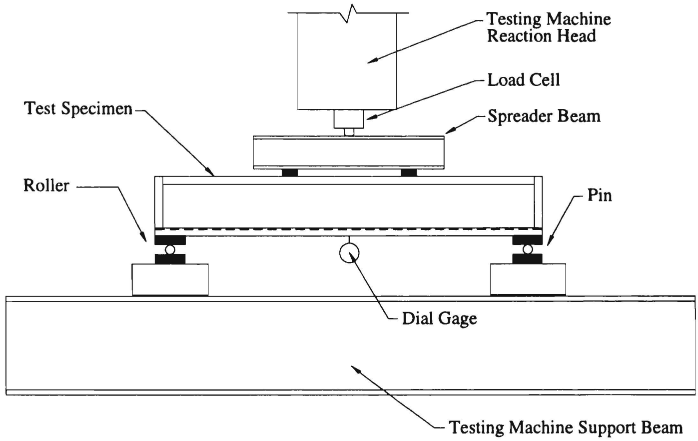

Figure 5. Schematic of Test Set-up

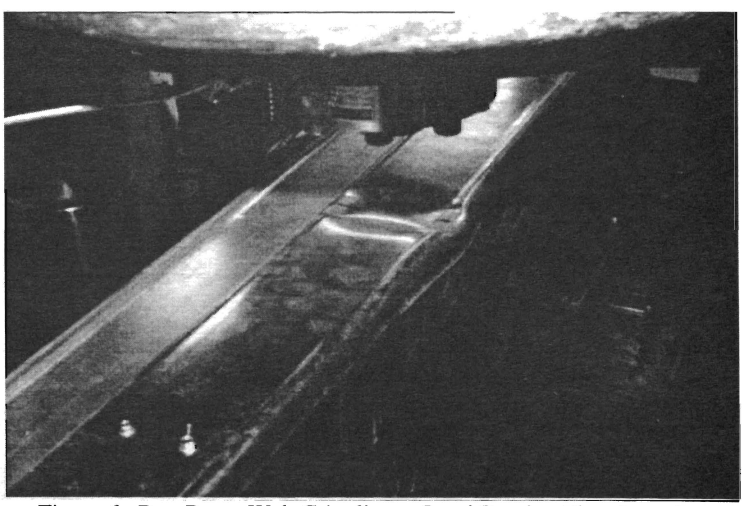

Figure 6. Box Beam Web Crippling at Load Bearing Plate Location

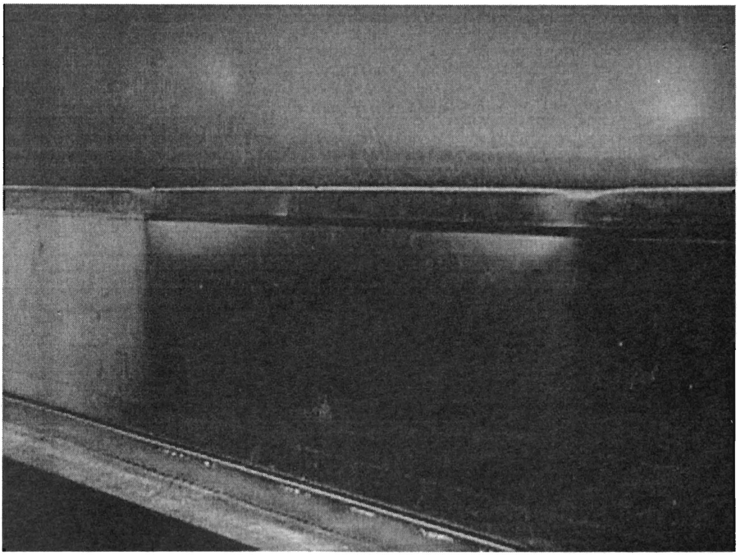

Figure 7. Box-Beam Web Crippling Failure at Two Load Bearing Points

Table 1. C-Section Properties for Strength Calculations

C-Section	t (in)	h (in)	h/t	R/t	N/t	F_y (ksi)	S_e (in^3)
600S162-43	0.0416	5.346	129	5.53	36.04	46.66	1.184
800S162-33	0.0324	7.654	236	5.30	46.27	47.00	0.582
800S162-54	0.0525	7.637	145	3.81	28.56	56.76	2.400
1000S162-54	0.0538	9.548	177	4.35	27.85	54.85	2.737
1200S162-68	0.0724	11.477	159	4.15	20.73	45.25	6.183
600S200-33	0.0346	5.555	161	4.08	43.35	48.60	0.481
600S200-43	0.0422	5.494	130	3.70	35.52	35.10	0.715
600S200-68	0.0665	5.497	83	2.12	22.57	55.30	1.061
800S200-54	0.0550	7.577	138	2.27	27.26	55.70	1.271
800S200-68	0.0692	7.377	107	1.88	21.68	53.88	1.803
1000S200-68	0.0667	9.371	141	2.11	22.50	65.50	1.941
1000S200-97	0.0957	9.313	97	1.47	15.68	62.52	3.488
1200S200-97	0.1019	11.316	111	1.23	14.72	58.41	4.957
600S162-33	0.0331	5.558	168	4.73	45.35	30.00	0.541
600S162-54	0.0531	5.659	107	2.35	28.24	52.40	0.881
800S162-43	0.0471	7.671	163	2.70	32.00	52.30	0.986

(1-inch = 25.4 mm; 1-ksi = 6.895 Mpa)

Table 2. Evaluation of Relationship Between P_t and P'_n

Test Specimen	P_t (kips)	P_n (kips)	Track t/ C-Section t	P'_n (kips)	P_t/P'_n
2x6x33 Box 1	2.898	1.360	1.001	3.130	0.926
2x6x33 Box 2	3.012	1.360	1.001	3.130	0.962
2x6x43 Box 1	3.470	1.475	0.820	2.781	1.248
2x6x43 Box 2	3.440	1.475	0.820	2.781	1.237
2x6x43 Box 3	4.690	3.891	0.627	5.615	0.835
2x6x68 Box 1	7.492	6.395	0.521	7.663	0.978
2x6x68 Box 2	7.406	6.395	0.521	7.663	0.966
2x8x43 Box 1	4.640	2.942	0.684	4.629	1.002
2x8x43 Box 2	4.850	2.942	0.684	4.629	1.048
2x8x54 Box 1	5.544	4.378	0.629	6.335	0.875
2x8x54 Box 2	5.550	4.378	0.629	6.335	0.876
2x8x68 Box 1	7.504	6.800	0.500	7.827	0.959
2x8x68 Box 2	7.474	6.800	0.500	7.827	0.955
TBox2x10x54x3-3	4.830	3.245	0.599	4.467	1.081
2x10x68 Box 1	8.154	7.395	0.519	8.832	0.923
TBox2x12x68x3.5-3	6.820	4.686	0.445	4.793	1.423
(1-kip = 1.118 kN)				Mean	1.018
				Standard Deviation	0.158
				Coeff. Of Variation	0.155

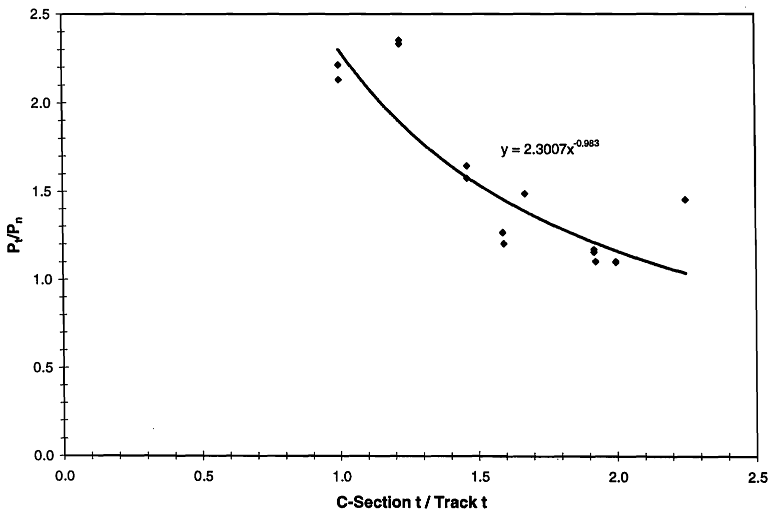

Figure 8. Power Curve for C-Section Thickness to Track Thickness Relationship

Table 3. Data for Box-Beam Statistical Analysis

Test Specimen	M_t/M_n	P_t/P'_n	Equation 4.13
2x6x33 Box 1	0.558	0.926	0.989
2x6x33 Box 2	0.580	0.962	1.028
2x6x33 Box 3	1.079	0.644	1.149
2x6x33 Box 4	0.953	0.730	1.122
2x6x33 Box 5	0.894	1.000	1.263
2x6x43 Box 1	0.622	1.248	1.247
2x6x43 Box 2	0.617	1.237	1.236
2x6x43 Box 3	0.614	0.835	0.966
2x6x43 Box 4	0.874	0.594	0.979
2x6x68 Box 1	0.575	0.978	1.035
2x6x68 Box 2	0.568	0.966	1.023
2x6x68 Box 3	1.078	0.660	1.159
2x8x33 Box 1	0.556	1.483	1.359
2x8x33 Box 2	0.533	1.421	1.303
2x8x33 Box 3	0.955	0.954	1.272
2x8x33 Box 4	0.966	0.965	1.287
2x8x43 Box 1	0.540	1.002	1.028
2x8x43 Box 2	0.565	1.048	1.075
2x8x43 Box 3	0.831	0.771	1.068
2x8x43 Box 4	0.835	0.774	1.073
2x8x54 Box 1	0.352	0.875	0.818
2x8x54 Box 2	0.353	0.876	0.819
2x8x54 Box 5	0.768	0.687	0.970
2x8x68 Box 1	0.347	0.959	0.871
2x8x68 Box 2	0.346	0.955	0.867
2x8x68 Box 3	0.727	0.722	0.966
2x10x68 Box 1	0.289	0.923	0.808
2x10x68 Box 2	0.875	0.622	0.998
2x10x97 Box 1	1.067	0.763	1.220
2x10x97 Box 2	0.278	0.896	0.783
2x12x97 Box 1	1.007	0.890	1.265
2x12x97 Box 2	0.255	0.869	0.750
TBox2x6x43x5-1	0.836	1.642	1.652
TBox2x10x54x3-3	0.289	1.081	0.913
TBox2x10x54x6-1	0.659	0.890	1.033
TBox2x12x68x3.5-3	0.256	1.423	1.119
TBox2x12x68x12-1	0.757	0.818	1.050
TBox2x12x68x12-2	0.733	0.792	1.016
		Mean	1.068
		Standard Deviation	0.187
		COV	0.175

Table 4. Box-Beam Header Interaction Data

Test Specimen	C-Sections	M_t[1] (k-ft)	M_n[2] (k-ft)	P_t[3] (k)	P'_n[4] (k)	M_t/M_n	P_t/P'_n
2x6x33 Box 1	600S200-33	2.174	3.896	2.898	3.130	0.558	0.926
2x6x33 Box 2	600S200-33	2.259	3.896	3.012	3.130	0.580	0.962
2x6x33 Box 3	600S200-33	4.202	3.896	2.017	3.130	1.079	0.644
2x6x33 Box 4	600S200-33	3.713	3.896	2.285	3.130	0.953	0.730
2x6x33 Box 5	600S162-33	2.420	2.706	2.420	2.420	0.894	1.000
2x6x43 Box 1	600S200-43	2.603	4.184	3.470	2.781	0.622	1.248
2x6x43 Box 2	600S200-43	2.580	4.184	3.440	2.781	0.617	1.237
2x6x43 Box 3	600S162-43	4.690	7.633	4.690	5.615	0.614	0.835
2x6x43 Box 4	600S162-43	6.670	7.633	3.335	5.615	0.874	0.594
2x6x68 Box 1	600S200-68	5.619	9.774	7.492	7.663	0.575	0.978
2x6x68 Box 2	600S200-68	5.555	9.774	7.406	7.663	0.568	0.966
2x6x68 Box 3	600S200-68	10.541	9.774	5.060	7.663	1.078	0.660
2x8x33 Box 1	800S162-33	2.535	4.557	3.380	2.280	0.556	1.483
2x8x33 Box 2	800S162-33	2.430	4.557	3.240	2.280	0.533	1.421
2x8x33 Box 3	800S162-33	4.350	4.557	2.175	2.280	0.955	0.954
2x8x33 Box 4	800S162-33	4.400	4.557	2.200	2.280	0.966	0.965
2x8x43 Box 1	800S162-43	4.640	8.591	4.640	4.629	0.540	1.002
2x8x43 Box 2	800S162-43	4.850	8.591	4.850	4.629	0.565	1.048
2x8x43 Box 3	800S162-43	7.140	8.591	3.570	4.629	0.831	0.771
2x8x43 Box 4	800S162-43	7.170	8.591	3.585	4.629	0.835	0.774
2x8x54 Box 1	800S200-54	4.158	11.800	5.544	6.335	0.352	0.875
2x8x54 Box 2	800S200-54	4.163	11.800	5.550	6.335	0.353	0.876
2x8x54 Box 5	800S200-54	9.063	11.800	4.350	6.335	0.768	0.687
2x8x68 Box 1	800S200-68	5.628	16.200	7.504	7.827	0.347	0.959
2x8x68 Box 2	800S200-68	5.606	16.200	7.474	7.827	0.346	0.955
2x8x68 Box 3	800S200-68	11.775	16.200	5.652	7.827	0.727	0.722
2x10x68 Box 1	1000S200-68	6.116	21.190	8.154	8.832	0.289	0.923
2x10x68 Box 2	1000S200-68	18.536	21.190	5.492	8.832	0.875	0.622
2x10x97 Box 1	1000S200-97	38.771	36.345	11.470	15.026	1.067	0.763
2x10x97 Box 2	1000S200-97	10.103	36.345	13.470	15.026	0.278	0.896
2x12x97 Box 1	1200S200-97	48.600	48.253	14.400	16.171	1.007	0.890
2x12x97 Box 2	1200S200-97	12.303	48.253	14.060	16.171	0.255	0.869
TBox2x6x43x5-1	600S162-43	3.850	4.605	4.605	2.804	0.836	1.642
TBox2x10x54x3-3	1000S162-54	3.623	12.542	4.830	4.467	0.289	1.081
TBox2x10x54x6-1	1000S162-54	8.268	12.542	3.975	4.467	0.659	0.890
TBox2x12x68x3.5-3	1200S162-68	5.968	23.310	6.820	4.793	0.256	1.423
TBox2x12x68x12-1	1200S162-68	17.640	23.310	3.920	4.793	0.757	0.818
TBox2x12x68x12-2	1200S162-68	17.077	23.310	3.795	4.793	0.733	0.792

[1] Test moment strength (1 k-ft = 1.356 kJ)

[2] Computed moment strength (1 k-ft = 1.356 kJ)

[3] Test web crippling strength (1 k = 4.448 kN)

[4] Computed web crippling strength using Equation 5 (1 k = 4.448 kN)

Table 5. Data for Box-Beam Statistical Analysis

Test Specimen	M_t/M_n	P_t/P'_n	Equation 7
2x6x33 Box 1	0.558	0.926	0.989
2x6x33 Box 2	0.580	0.962	1.028
2x6x33 Box 3	1.079	0.644	1.149
2x6x33 Box 4	0.953	0.730	1.122
2x6x33 Box 5	0.894	1.000	1.263
2x6x43 Box 1	0.622	1.248	1.247
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2x8x33 Box 3	0.955	0.954	1.272
2x8x33 Box 4	0.966	0.965	1.287
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2x8x54 Box 5	0.768	0.687	0.970
2x8x68 Box 1	0.347	0.959	0.871
2x8x68 Box 2	0.346	0.955	0.867
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2x10x68 Box 2	0.875	0.622	0.998
2x10x97 Box 1	1.067	0.763	1.220
2x10x97 Box 2	0.278	0.896	0.783
2x12x97 Box 1	1.007	0.890	1.265
2x12x97 Box 2	0.255	0.869	0.750
TBox2x6x43x5-1	0.836	1.642	1.652
TBox2x10x54x3-3	0.289	1.081	0.913
TBox2x10x54x6-1	0.659	0.890	1.033
TBox2x12x68x3.5-3	0.256	1.423	1.119
TBox2x12x68x12-1	0.757	0.818	1.050
TBox2x12x68x12-2	0.733	0.792	1.016
		Mean	1.068
		Standard Deviation	0.187
		COV	0.175

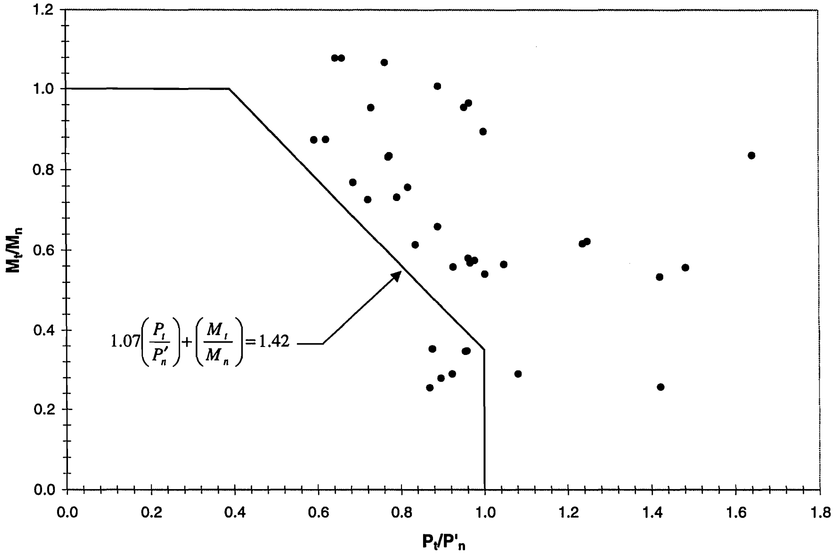

Figure 9. Box-Beam Interaction Plot using P'_n and Equation 3

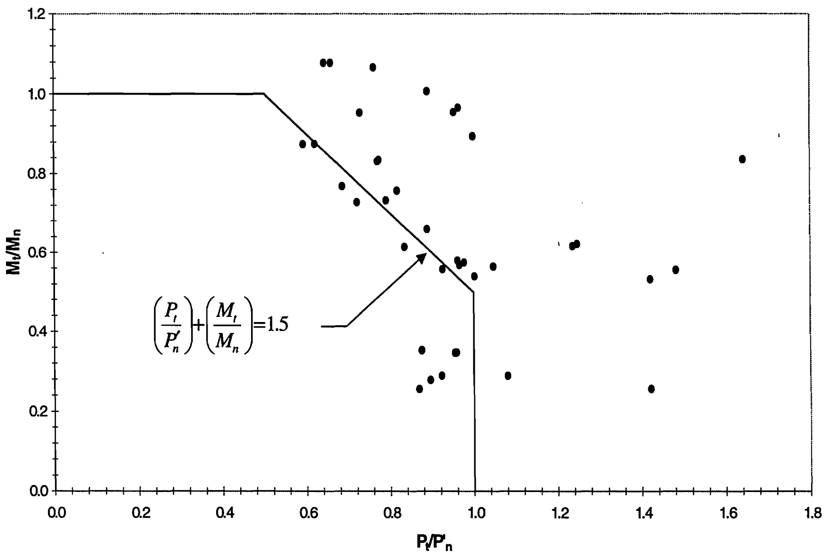

Figure 10. Box-Beam Interaction Plot using P'_n and Equation 6